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Effects of three types of soil amendments on yield and soil nitrogen balance of maize–wheat rotation system in the Hetao Irrigation Area, China

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Abstract: Excessive fertilization combined with unreasonable irrigation in farmland of the Hetao Irrigation Area (HIR), China, has resulted in a large amount of nitrogen (N) losses and agricultural non-point source pollution. Application of soil amendments has become one of the important strategies for reducing N losses of farmland. However, there is still no systematic study on the effects of various soil amendments on N losses in the HIR. In this study, three types of soil amendments (biochar, bentonite and polyacrylamide) were applied in a maize–wheat rotation system in the HIR during 2015–2017. Yields of maize and wheat, soil NH₃ volatilization, N₂O emission and NO₃⁻ leaching were determined and soil N balance was estimated. The results showed that applications of biochar, bentonite and polyacrylamide significantly increased yields of maize by 9.2%, 14.3% and 13.3%, respectively, and wheat by 9.2%, 16.6% and 12.3%, respectively, compared with the control (fertilization alone). Applications of biochar, bentonite and polyacrylamide significantly reduced soil N leaching by 23.1%, 35.5% and 27.1%, soil NH₃-N volatilization by 34.8%, 52.7% and 37.8%, and soil N surplus by 23.9%, 37.4% and 30.6%, respectively. Applications of bentonite and polyacrylamide significantly reduced N₂O-N emissions from soil by 37.3% and 35.8%, respectively, compared with the control. Compared with application of biochar, applications of bentonite and polyacrylamide increased yields of maize and wheat by 5.1% and 3.5%, respectively. Our results suggest that soil amendments (bentonite and polyacrylamide) can play important roles in reducing N losses and increasing yield for the maize–wheat rotation system in the HIR, China.

Keywords: biochar; bentonite; polyacrylamide; maize; nitrogen loss; nitrogen balance; wheat

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1 Introduction

Nitrogen (N) fertilizer is important for crop production in agriculture (Spiertz, 2010; Liu et al., 2013). It is estimated that the use of mineral N fertilizer accounted for about 30%–50% increase in crop yield (Ni et al., 2013; Lin et al., 2016). However, over use of N fertilizer that is a common

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practice in agriculture can result in significant N losses. Moreover, over use of N fertilizer is responsible for air pollution, eutrophication and groundwater pollution (Jussy et al., 2004; Sutton et al., 2011; Yang et al., 2015; Shang et al., 2016). Therefore, effective measures to reduce N losses in agriculture have received considerable attentions in various areas, especially in irrigated area (Cameron et al., 2013; Geng et al., 2015).

N losses in agriculture are mainly influenced by climatic and soil conditions. However, effective agricultural practices play vital roles in reducing N losses. Recently, studies have shown that soil amendments such as biochar, silicate minerals (bentonite) and organic polymers (polyacrylamide) could effectively reduce N losses (Golbashy et al., 2017; Yang et al., 2017). The reason is that the larger specific surface area and functional groups of biochar increase the adsorption capacity of soil inorganic N and significantly reduce the substrate concentrations of nitrification and denitrification (Clough et al., 2013; Cayuela et al., 2014; Thies et al., 2015). Similarly, polyacrylamide and bentonite are able to adsorb N and to release N slowly, due to the network structure formed by the interaction of polyacrylamide and soil, special structural characteristics and physicochemical property of bentonite (Singh et al., 2010; Qin et al., 2012; Abrol et al., 2013; Geng et al., 2016).

Hetao Irrigation Area (HIR) is located in Northwest China, belonging to arid and semi-arid areas (Kerschbaumer et al., 2015), and is one of the three major irrigation areas in China and an important area in China for cereal production such as wheat, maize and cash crop like sunflower (Xue et al., 2017). However, application of N fertilization in the HIR has been rapidly increasing, and has reached more than 500 kg N/hm². The over use of N fertilizer combined with flooding irrigation has aggravated agricultural non-point source (ANPS) pollution in the HIR (Wu et al., 2017). Nitrate concentration of groundwater has exceeded 20 mg/L in the HIR, which was higher than the limit of 10 mg/L as the maximum safety level for drinking water. Nitrate leaching from farmland is considered as the major contribution to groundwater N contamination (Wu et al., 2017). Furthermore, Xu et al. (2012) and Wang et al. (2016) showed that flooding irrigation can also significantly increase N₂O and NH₃ emissions compared with water-saving irrigation. Therefore, N losses of farmland in the HIR should be investigated. Since ANPS pollution of farmland in the HIR is increasing, we hypothesized that soil amendments provides an opportunity to increase crop yield and reduce N losses of farmland in the HIR.

Therefore, the objectives of this study were to apply soil amendments (biochar, bentonite and polyacrylamide) under optimal N fertilization for a 2-year maize and 1-year wheat rotation system in the HIR, to investigate the effects of different soil amendments on crop (maize and wheat) yield and soil N losses.

2 Materials and methods

2.1 Study area

The study area (40°26'–41°13'N, 106°34'–107°34'E) belonging to the HIR was located in Hanggin Rear Banner, Bayannur City, Inner Mongolia Autonomous Region, China. The soil of experimental site is mainly sulfate chlorinated salinity soil. The basic physical and chemical properties of the top soil layer (0–20 cm) were as follows: pH, 8.20; total N, 1.63 g/kg; NO₃⁻-N, 7.40 mg/kg; and NH₄⁺-N, 3.20 mg/kg.

2.2 Materials

Maize (*Zea mays* L. cv. Internal Single 314) and wheat (*Triticum aestivum* L. cv. Yongliang 4) were used in this study.

Straw biochar was purchased from Liaoning Jinhefu Agricultural Development Co., Ltd. The basic physical and chemical properties of straw biochar were as follows: pH, 9.67; carbon content, 70.38%; hydrogen content, 1.68%; sulfur content, 0.78%; N content, 1.53%; and ash content, 31.80%.

Bentonite was purchased from Inner Mongolia Tianyu Co., Ltd. with a size of 325-mesh and

CEC (cation exchange capacity) was 78 cmol/kg. The pH was 8.26. Polyacrylamide was purchased from Eisen Company of France with a high molecular weight (1.2×10^6 g/mol).

Fertilizers of diammonium phosphate (18% N and 16% P_2O_5), common urea (46% N) and potassium sulfate (50% K_2O) were purchased from Inner Mongolia Gengyu Chemical Co. Ltd.

2.3 Experimental design

There were four treatments in this study, i.e., formula fertilization (F), formula fertilization+biochar (FC), formula fertilization+bentonite (FB) and formula fertilization+polyacrylamide (FP). Treatments were arranged in a randomized block design with three replications. Size of plot was 133 m² (19 m×7 m) with 30 cm ridge between plots.

Spacing of maize was 20 cm between plants in each planting row and 60 cm between rows. Planting density of maize was 8.25×10^4 strains/hm². Spacing of wheat was 2 cm between plants in each planting row and 12 cm between rows. Wheat seed dosage was 450 kg/hm².

Soil amendments and fertilizer were incorporated into the 0–20 cm top soil layer. Rates of biochar, bentonite and polyacrylamide were 1500, 6000 and 75 kg/hm², respectively. The overview of experimental dates and fertilizer rates was shown in Table 1. There was once harvest within a year in the HIR.

Table 1 Sowing, harvest, fertilizing and irrigation dates (date pattern of mm/dd/yy is used) and fertilizer rate in the Hetao Irrigation Area during 2015–2017

Crop	Sowing date (mm/dd/yy)	Harvest date (mm/dd/yy)	Fertilizing date and type (mm/dd/yy)	Fertilizer rate (kg/hm ²)	Irrigation date (mm/dd/yy)
Maize	04/27/2015	09/16/2015	04/25/2015 (BF)	637.5 (DP)+187.5 (PS)	
			06/19/2015 (TD)	304 (CU)	06/20/2015
			07/09/2015 (TD)	152 (CU)	07/10/2015
					08/15/2015
					11/08/2015
Maize	05/02/2016	09/20/2016	04/30/2016 (BF)	637.5 (DP)+187.5 (PS)	
			06/21/2016 (TD)	304 (CU)	06/22/2016
			07/10/2016 (TD)	152 (CU)	07/11/2016
					08/10/2016
					11/12/2016
Wheat	03/24/2017	07/15/2017	03/23/2017 (BF)	255 (DP)+75 (PS)	
			05/06/2017 (TD)	225 (CU)	05/07/2017
			05/28/2017 (TD)	120 (CU)	05/29/2017
					06/13/2017
					06/30/2017
					11/03/2017

Note: BF, basal fertilizer; TD, top dressing fertilizer; DP, diammonium phosphate; PS, potassium sulfate; CU, common urea.

2.4 Soil and plant sampling and chemical analysis

2.4.1 Irrigation and rainfall collection

Rainfall collection device was a square polypropylene tray (60 cm×30 cm×10 cm). The tray was horizontally fixed on a bracket of 30-cm height in each plot. Rainfall amount was measured after each rain event, and then the water sample from rainfall was taken to determine contents of NH_4^+-N and NO_3^--N . Similarly, water sample from irrigation was also determined. Total N depositions from irrigation and rainfall were then calculated.

2.4.2 Determination of plant sampling and total N content

Crops (maize and wheat) were harvested at maturity in each plot. Plant grain and straw samples were oven-dried at 105°C for 30 min, and then at 80°C for 72 h to determine plant water content

(Yao et al., 2007). Dried samples were ground through a 0.15-mm sieve, and used for total N analysis. Total N content of plant was determined using a flow analyzer (Model AA3, Bran+Luebbe, Germany) after wet digestion with $\text{H}_2\text{SO}_4\text{-H}_2\text{O}_2$.

2.4.3 Determination of $\text{NH}_3\text{-N}$ volatilization

$\text{NH}_3\text{-N}$ volatilization was determined by the Venting method (Wang et al., 2002). $\text{NH}_3\text{-N}$ volatilization collection device was made of polyvinyl chloride plastic tube (15 cm in diameter and 10 cm in height). Two sponges of 2 cm in thickness and 15 cm in diameter were placed in the plastic tube, after absorbing 15 mL of the glycerol phosphate solution (50 mL phosphoric acid+40 mL glycerol, constant volume to 1000 mL). The lower sponge was 5 cm from the bottom of tube and the upper sponge was flat with the top of tube. Three $\text{NH}_3\text{-N}$ volatilization devices were placed in random locations for each plot and samples were taken at 08:00 (LST). $\text{NH}_3\text{-N}$ samples were daily measured for first 2 d after fertilization and then once a week afterwards. The lower sponge was loaded into a 500-mL plastic shaker and extracted with 2 mol/L KCl solution. Content of $\text{NH}_4^+\text{-N}$ in the extract solution was determined by the flow analyzer. $\text{NH}_3\text{-N}$ volatilization rate was derived from the following equation:

$$V = (M / (A \times D)) \times 10^{-2}, \quad (1)$$

where V is the $\text{NH}_3\text{-N}$ volatilization rate ($\text{kg}/(\text{hm}^2\cdot\text{d})$); M is the $\text{NH}_3\text{-N}$ content absorbed by each sponge (mg); A is the cross-sectional area (m^2) of the capture device; and D is the time of each successive measurement (d). Cumulative volatilization of $\text{NH}_3\text{-N}$ ($\text{kg N}/\text{hm}^2$) was calculated by summing daily $\text{NH}_3\text{-N}$ volatilization during growing period.

2.4.4 $\text{N}_2\text{O-N}$ gas collection and monitoring

$\text{N}_2\text{O-N}$ emission was determined by the static chamber-gas chromatographic method (Wang et al., 2017). The sampling system consists of two parts: box and pedestal. The box was made of 1.2-mm thick stainless steel plate, and the size was 50 cm×50 cm×50 cm. A three-way valve is installed in the center of the box and has a thermometer beside it to monitor air temperature. Outer layer of the box was wrapped with foam for holding air temperature. A small fan was installed on the top of the box for mixing gas. The pedestal was located at random position in each plot, which size was 50 cm×50 cm×15 cm. The pedestal was inserted into a 12-cm soil layer. Inside of the pedestal didn't grow crops and the pedestal was no longer moved during whole growing period. There was a sink on the pedestal for water injection to seal the chamber. $\text{N}_2\text{O-N}$ samples were daily measured for 2 d after fertilization and then once a week afterwards. Four gas samples from each box were collected using a syringe at 10 min intervals between 09:00 and 11:30 on every sampling day. Synchronous with gas collection, soil temperature (by thermometer) and soil moisture (by oven drying method) in the 0–20 cm soil layer were monitored. $\text{N}_2\text{O-N}$ samples were analyzed with a Picarro Cavity Ring-Down Spectroscopy Analyzer (Model G2308, Picarro Inc., Santa Clara, California). We calculated daily N_2O emission based on the following linear regression equation:

$$FE = \frac{M}{V_0} \times \frac{\Delta C}{\Delta t} \times \frac{273}{(273+T)} \times H, \quad (2)$$

where FE is the gas emission of N_2O ($\text{mg}/(\text{m}^2\cdot\text{h})$); M is the mole mass of N_2O (g/mol); V_0 is the volume of N_2O under standard condition (mL); $\Delta C/\Delta t$ is the slope of linear regression of gas concentration with time approaching zero; T is the temperature ($^{\circ}\text{C}$); and H is the chamber height above water surface (cm). Cumulative $\text{N}_2\text{O-N}$ emission ($\text{kg N}/\text{hm}^2$) was calculated by summing amount of daily $\text{N}_2\text{O-N}$ emission.

2.4.5 Leaching water collection and determination of N leaching

Leaching water was collected by the method of *in situ* lysimeter (Cameron et al., 2013). Drainage collector used in the experiment consists of a polypropylene disc (collector) (60 cm×30 cm×10 cm) and a 25-L polypropylene bucket (sample storage) connected with plastic pipes (Weihermüller et al., 2007). Filter was installed in plastic nozzle to prevent the soil from entering bucket. A 1.5-m deep pit was dug in the center of the plot, and the bucket was placed at the lowest point. A hole of 60 cm×10 cm×30 cm at the 1-m horizon in the soil section was used to place the

collector. A 100-mesh nylon net was fixed on the top of collector, so that the upper surface of collector was tightly bonded with the upper soil layer. Plastic tube in polypropylene barrel was pulled up to 50 cm above the ground, and soil layered landfill. The upper end of plastic tube access to sampling bottle (10 L), and sampling bottle was connected to a buffer bottle (2 L) and followed by a vacuum pump. The amount of water leached was measured after irrigation and harvest. A certain volume of water sample was collected and stored at low temperature. Concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ were determined by the flow analyzer on the next day. Total leached N content (kg N/hm^2) was calculated by summing amount of N leaching after irrigation and harvest.

2.4.6 Soil sampling

After plants were harvested, samples were collected at 20-cm intervals from the 0–100 cm soil layer using a soil auger (5 cm in diameter). Each plot had two soil cores taken diagonally, and samples of the same depth were mixed and homogenized for each plot. Soil was extracted with 2 mol/L KCl (soil to water ratio 1:10), and $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ contents were determined by the flow analyzer. Total N in soil was determined by the semi-trace Kaiser method. Soil water mixture (1:5) was analyzed for pH by the potentiometric method.

2.5 Calculation of soil N balance

In this study, soil N balance was calculated by the following equation (Ju et al., 2006):

$$\text{N surplus} = \text{input components (N fertilizer + N from irrigation + N from rainfall)} - \text{output components (N removed by aboveground plant parts)} \quad (3)$$

where N surplus (kg N/hm^2) represents the N that was lost by ammonia volatilization, $\text{N}_2\text{O-N}$ emission, nitrate leaching and/or N stored in various soil fractions.

2.6 Statistical analyses

All statistical analyses were performed using the SAS 9.1 (SAS Institute Inc., USA) and Microsoft Excel 2010 for Windows. Least significant difference (LSD) test was done for multiple comparisons between means. One-way analysis of variance (ANOVA) was used to analyze effects of three types of amendments on yield, $\text{NH}_3\text{-N}$ volatilization, $\text{N}_2\text{O-N}$ emission and soil N leaching during experimental period. We assessed significances of tests or analyses based on the probability level of 0.05.

3 Results

3.1 Effects of soil amendments on yield, straw biomass and plant N uptake

Results in Table 2 showed that, compared with application of F, treatments with soil amendments (i.e., FC, FB and FP) significantly increased yield and straw biomass for both maize and wheat ($P < 0.05$). During the period from 2015 to 2016, average yields of maize increased by 9.2% in FC, 14.3% in FB and 13.3% in FP, respectively, and average straw biomasses of maize increased by 9.3% in FC, 15.0% in FB and 12.7% in FP, respectively, compared with that in F. In 2017, yields of wheat increased by 9.2% in FC, 16.6% in FB and 12.3% in FP, while straw biomass increased by 12.3% in FC, 20.3% in FB and 14.6% in FP, respectively, compared with that in F.

Three types of soil amendments significantly increased plant N uptake ($P < 0.05$). The plant N uptakes increased by 10.5% in FC, 14.8% in FB and 13.5% in FP, respectively, compared with that in F.

3.2 Effects of soil amendments on soil N losses

3.2.1 Effect of soil amendments on soil N leaching

Concentrations of $\text{NO}_3^-\text{-N}$ and $\text{NH}_4^+\text{-N}$ in the leaching solution decreased with time (Fig. 1). The highest values of $\text{NO}_3^-\text{-N}$ and $\text{NH}_4^+\text{-N}$ in the leaching solution occurred after the first irrigation. $\text{NO}_3^-\text{-N}$ concentration was within the range from 29.1 to 81.1 mg/L and $\text{NH}_4^+\text{-N}$ concentration was within the range from 5.1 to 9.4 mg/L. The main form of leached N is $\text{NO}_3^-\text{-N}$, accounting for about 85%. During 2015–2017, amounts of N leaching were significantly lower in FC, FB and FP than in F (Table 3). Compared with that in F, N leaching amounts were reduced by 23.1% in FC, 35.5% in FB and 27.1% in FP.

Table 2 Effects of different soil amendments on yield, straw biomass and plant N uptake in the Hetao Irrigation Area during 2015–2017

Year	Crop	Treatment	Yield (kg/hm ²)	Straw biomass (kg/hm ²)	Plant N uptake (kg N/hm ²)
2015	Maize	F	10,409±619 ^c	12,327±438 ^b	249.8±16.0 ^b
		FC	11,427±342 ^b	13,633±833 ^a	279.5±16.1 ^a
		FB	12,317±352 ^a	14,786±728 ^a	291.3±16.5 ^a
		FP	11,530±403 ^{ab}	13,890±608 ^a	282.6±2.4 ^a
2016	Maize	F	8872±240 ^b	10,791±295 ^b	231.3±5.9 ^b
		FC	9630±427 ^a	11,625±498 ^a	251.6±4.4 ^a
		FB	9712±298 ^a	11,805±297 ^a	258.0±6.2 ^a
		FP	10,316±528 ^a	12,157±314 ^a	263.8±13.6 ^a
2017	Wheat	F	5423±272 ^b	5352±353 ^b	156.9±9.9 ^b
		FC	5923±184 ^a	6011±335 ^a	173.7±6.8 ^a
		FB	6325±132 ^a	6437±328 ^a	183.3±8.8 ^a
		FP	6091±217 ^a	6131±210 ^a	178.0±5.8 ^a

Note: F, formula fertilization; FC, formula fertilization+biochar; FB, formula fertilization+bentonite; FP, formula fertilization+polyacrylamide. The abbreviations are the same as in Tables 3–6. Means with different lowercase letters within the same column and year are significantly different at $P<0.05$ level. Mean±SD; $n=3$.

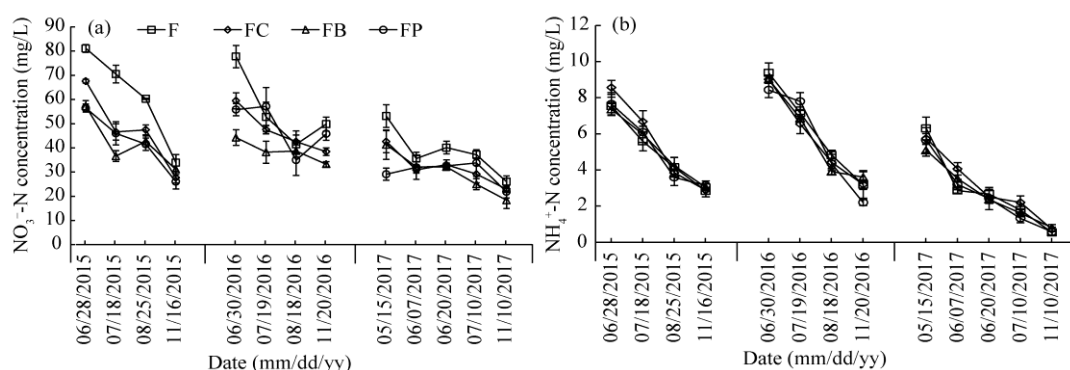


Fig. 1 Variations of NO₃⁻-N (a) and NH₄⁺-N (b) concentrations in the leaching solution under different soil amendments in the Hetao Irrigation Area during 2015–2017. Date pattern of mm/dd/yy is used. F, formula fertilization; FC, formula fertilization+biochar; FB, formula fertilization+bentonite; FP, formula fertilization+polyacrylamide. The abbreviations are the same as in Figures 2 and 3. Error bars represent standard deviations; $n=3$.

3.2.2 Effects of soil amendments on NH₃-N volatilization and N₂O-N emission

NH₃-N volatilization reached a maximum within one week after fertilization, and then decreased and maintained at a lower level until the next irrigation or fertilizer application (Fig. 2). Application of N fertilizer to soil significantly promoted NH₃-N volatilization.

Cumulative NH₃-N volatilization is shown in Table 4. Compared with F, FC, FB and FP significantly reduced soil cumulative NH₃-N volatilization ($P<0.05$), i.e., average cumulative NH₃-N volatilization decreased by 34.8% in FC, 52.7% in FB and 37.8% in FP. The greater reduction was observed in FB (Table 4).

Pattern of N₂O-N emission rate with time is different from that of NH₃-N volatilization (Fig. 3). The peak of N₂O-N emission rate appeared only 4–8 d after application of urea. Because irrigation provides an anaerobic condition for denitrification, applications of urea and irrigation significantly enhanced N₂O-N emission. Cumulative N₂O-N emissions in FB and FB were significantly lower than those in F and FC ($P<0.05$). However, there was no significant difference between F and FC. Compared with that in F, cumulative emissions of N₂O-N were decreased by 37.3% in FB and 35.8% in FP (Table 4).

Table 3 Effects of different soil amendments on N leaching volume and N leaching amount in the Hetao Irrigation Area during 2015–2017

Year	Crop	Treatment	N leaching volume (m ³ /hm ²)	N leaching amount (kg N/hm ²)
2015	Maize	F	1022.2±15.9 ^a	69.5±1.5 ^a
		FC	991.0±28.8 ^{ab}	53.3±0.6 ^b
		FB	951.3±15.6 ^b	44.5±1.8 ^c
		FP	956.3±26.5 ^b	45.9±3.9 ^c
2016	Maize	F	1395.7±64.4 ^a	86.9±5.7 ^a
		FC	1230.8±72.8 ^b	66.9±5.9 ^b
		FB	1215.4±91.7 ^b	54.5±3.3 ^c
		FP	1249.3±28.0 ^b	68.6±4.3 ^b
2017	Wheat	F	1294.4±47.3 ^a	54.5±7.1 ^a
		FC	1183.9±61.1 ^{ab}	41.9±2.1 ^b
		FB	1132.5±90.8 ^b	37.1±4.8 ^b
		FP	1191.5±56.9 ^{ab}	39.1±3.6 ^b

Note: Different lowercase letters within the same column and year are significantly different at $P<0.05$ level. Mean±SD; $n=3$.

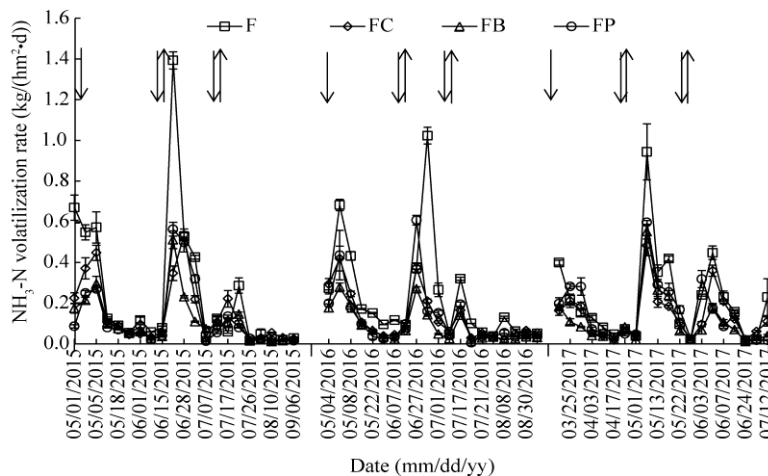


Fig. 2 Variation of NH₃-N volatilization rate under different soil amendments in the Hetao Irrigation Area during 2015–2017. Date pattern of mm/dd/yy is used. Downward arrow denotes fertilizing date and upward arrow denotes irrigation date. Error bars represent standard deviations; $n=3$.

Table 4 Effects of different soil amendments on cumulative NH₃-N volatilization and cumulative N₂O-N emission in the Hetao Irrigation Area during 2015–2017

Year	Crop	Treatment	Cumulative NH ₃ -N volatilization (kg N/hm ²)	Cumulative N ₂ O-N emission (kg N/hm ²)
2015	Maize	F	21.07±1.74 ^a	3.63±0.31 ^a
		FC	13.93±0.84 ^b	3.20±0.39 ^a
		FB	10.26±1.15 ^c	2.06±0.11 ^b
		FP	11.76±0.50 ^c	2.00±0.37 ^b
2016	Maize	F	19.84±2.07 ^a	3.85±0.23 ^a
		FC	11.75±0.31 ^b	4.29±0.26 ^a
		FB	8.20±0.36 ^c	2.28±0.22 ^b
		FP	11.14±0.57 ^b	2.52±0.34 ^b
2017	Wheat	F	17.09±1.66 ^a	1.98±0.10 ^a
		FC	12.13±1.64 ^{bc}	2.07±0.35 ^a
		FB	8.96±0.91 ^c	1.59±0.11 ^b
		FP	13.17±2.26 ^b	1.55±0.15 ^b

Note: Different lowercase letters within the same column and year are significantly different at $P<0.05$ level. Mean±SD; $n=3$.

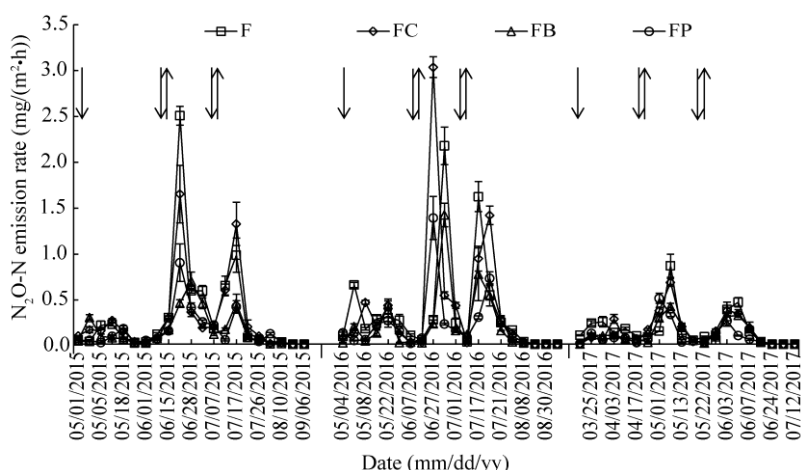


Fig. 3 Variation of N_2O -N emission rate under different soil amendments in the Hetao Irrigation Area during 2015–2017. Date pattern of mm/dd/yy is used. Downward arrow denotes fertilizing date and upward arrow denotes irrigation date. Error bars represent standard deviations; $n=3$.

3.3 Effects of soil amendments on soil N concentrations and soil pH

During 2015–2017, soil amendments did not affect soil total N and NH_4^+ -N concentration, but significantly increased soil NO_3^- -N concentration ($P<0.05$; Table 5). Compared with that in F, the NO_3^- -N concentrations were increased by 13.0% in FC, 14.1% in FB and 11.7% in FP. Soil pH was significantly higher in FC than in F ($P<0.05$; Table 5). However, there was no difference in soil pH among FB, FP and F. Compared with that in F, soil pH in FC increased, e.g., soil pH increased by 2.7% in 2015, 3.6% in 2016 and 5.4% in 2017. Biochar application increased soil pH from 8.20 to 8.63.

Table 5 Effects of different soil treatments on soil total N, NO_3^- -N, NH_4^+ -N concentrations and pH in the Hetao Irrigation Area during 2015–2017

Year	Crop	Treatment	Total N (g/kg)	NO_3^- -N (mg/kg)	NH_4^+ -N (mg/kg)	pH
2015	Maize	F	1.65 ± 0.05^a	17.10 ± 0.65^b	5.46 ± 1.02^a	8.16 ± 0.07^b
		FC	1.64 ± 0.04^a	18.43 ± 0.33^a	5.82 ± 0.52^a	8.38 ± 0.05^a
		FB	1.69 ± 0.04^a	18.98 ± 0.88^a	5.37 ± 0.71^a	8.15 ± 0.08^b
		FP	1.62 ± 0.04^a	18.70 ± 0.66^a	5.01 ± 0.36^a	8.25 ± 0.08^{ab}
2016	Maize	F	1.68 ± 0.03^a	13.88 ± 0.33^b	6.15 ± 0.73^a	8.24 ± 0.10^b
		FC	1.71 ± 0.08^a	15.54 ± 0.79^a	5.84 ± 0.72^a	8.54 ± 0.15^a
		FB	1.70 ± 0.04^a	16.05 ± 1.05^a	5.76 ± 0.43^a	8.17 ± 0.08^b
		FP	1.67 ± 0.04^a	15.65 ± 0.84^a	6.22 ± 0.42^a	8.21 ± 0.05^b
2017	Wheat	F	1.63 ± 0.06^a	11.43 ± 0.82^b	5.00 ± 0.61^a	8.19 ± 0.09^b
		FC	1.69 ± 0.07^a	13.95 ± 0.64^a	5.37 ± 0.80^a	8.63 ± 0.17^a
		FB	1.69 ± 0.06^a	13.36 ± 0.63^a	4.89 ± 0.48^a	8.21 ± 0.08^b
		FP	1.66 ± 0.06^a	13.02 ± 0.99^a	4.46 ± 0.38^a	8.25 ± 0.08^b

Note: Different lowercase letters within the same column and year are significantly different at $P<0.05$ level. Mean \pm SD; $n=3$. The above data come from the top soil layer (0–20 cm).

3.4 Soil N balance

There were three N sources as inputs in this experiment, i.e., mineral N fertilizer, irrigation and rainfall (Table 6). N input of maize–wheat rotation system ranged from 223.90 to 342.80 kg N/hm², in which N input for maize ranged from 340.20–342.80 kg N/hm², and that for wheat was 223.90–226.70 kg N/hm². N output was 229.90–344.20 kg N/hm², in which N output of maize was 240.60–274.60 kg N/hm², and that of wheat was 156.90–183.30 kg N/hm². N surplus of wheat was significantly lower than that of maize, mainly due to the lower N application rate for

wheat. FC, FB and FP significantly reduced N surplus that was respectively 23.9%, 37.4% and 30.6% lower than that in F. Consequently, lower soil N losses were also observed (Table 6).

Table 6 N input, output, soil N balance and soil N losses in the Hetao Irrigation Area during 2015–2017

N resource	Maize				Wheat			
	F	FC	FB	FP	F	FC	FB	FP
N input (kg N/hm ²)								
Irrigation	16.10	17.30	14.75	16.70	20.20	20.20	18.80	21.60
Rainfall	1.04	1.04	1.04	1.04	0.54	0.54	0.54	0.54
Total input	341.60	342.80	340.20	342.20	225.40	225.40	223.90	226.70
N output (kg N/hm ²)								
Plant uptake	240.60	265.50	274.60	273.20	156.90	173.70	183.30	178.00
Soil N balance (kg N/hm ²)								
N surplus	101.00	77.30	65.60	690.00	68.50	51.70	40.60	48.70
Soil N losses (kg N/hm ²)								
N leaching	78.20	60.10	49.50	57.30	54.50	41.90	37.10	39.10
NH ₃ -N volatilization	20.50	12.80	9.20	11.50	17.10	12.10	9.00	13.20
N ₂ O-N emission	3.70	3.80	2.20	2.30	2.00	2.10	1.60	1.60
Total N loss	102.40	76.70	60.90	71.10	73.60	56.10	47.70	53.90

4 Discussion

4.1 Effects of soil amendments on soil N losses and yield

Our results clearly showed that three types of soil amendments significantly increased the yields of maize and wheat (Table 2) and significantly reduced soil N surplus (Table 6). The performance of bentonite and polyacrylamide was the best. For example, compared with FC, FB and FP increased the yields of maize and wheat by 5.1% and 3.5% (Table 2) and decreased soil N surplus by 17.7% and 8.8% (Table 6), respectively.

It is known that biochar, bentonite, and polyacrylamide play important roles in reducing soil N losses and increasing N utilization rate. Thangarajan et al. (2017) found that application of biochar reduced both N₂O and NH₃ emissions by 23% and 43%, respectively. Nguyen et al. (2017) suggested that biochar can enhance adsorption of NO₃⁻-N and effectively reduce soil N leaching. Our study showed similar results of significant reduction in NH₃-N volatilization and soil N leaching by the application of biochar (Tables 3 and 4), but there was no effect on N₂O-N emission (Table 4). Biochar adsorption of inorganic N in soil is the main reason for reducing NH₃-N volatilization and soil N leaching. The adsorption capacity of biochar on soil inorganic N is derived from functional groups (Nguyen et al., 2017). Acid functional groups include carboxylic, hydroxyl, lactone and lactol that have a negative charge and absorb the soil's NH₄⁺-N by electrostatic attraction (Hina et al., 2010; Spokas et al., 2012). Functional group of ketones and pyrones can promote adsorption of NO₃⁻-N by biochar (Monte-Moran et al., 2004). Hydrogen bond on the surface of biochar can also be combined with NO₃⁻-N in the soil (Mukherjee et al., 2011; Kammann et al., 2015). Effect of biochar on fixation of NO₃⁻-N also reduced the nitrification effect to some extent. Adsorption of inorganic N in the soil by biochar increases soil N content, delays soil nitrification, satisfies N demand in the later stages of crop, improves N nutrition status in crop and further increases the crop production (Kammann et al., 2015; Nguyen et al., 2017). However, our study found that application of biochar could enhance soil pH (Table 3). Dandie et al. (2011) reported that nitrate reduction bacteria in soil were positively correlated with soil pH, and increase of pH could significantly increase the number of bacteria. Dramatic change in soil moisture conditions during irrigation may form a strict anaerobic environment that increases the number of nitrite reduction bacteria, thus improving the process of denitrification and leading to an increase in the transformation of NO₂⁻ into NO. Consequently, biochar

application in this study was not able to suppress soil N_2O -N emission.

This study found that application of bentonite could significantly reduce NH_3 -N volatilization, N_2O -N emission and soil N leaching (Tables 3 and 4), mainly due to its adsorption characteristic of N. The main component of bentonite is montmorillonite that is a 2:1 layered phyllosilicate clay whose inter layer ions can exchange with NH_4^+ -N (Golbashy et al., 2017). Under a wet condition, free NH_4^+ -N in soil is more easily fixed by bentonite to form the slow-released N (Solihin et al., 2011). Secondly, amount of bentonite CEC used in the experiment is 78 cmol/kg, which is about 6 times higher than that of farmland in the HIR. After a large amount of bentonite was added, soil CEC was improved and adsorption of NH_4^+ -N was enhanced. Adsorption of bentonite on soil NH_4^+ -N significantly reduces soil NH_3 -N volatilization and reduces the substrate concentration of nitrification at the same time, thus significantly inhibiting N_2O -N emission and soil N leaching. This is consistent with the findings of Qin et al. (2012) and Yang et al. (2017). Crop yields can be significantly increased due to the slow release of soil N by bentonite (Yang et al., 2017).

The results of the present study showed that compared with fertilizer application alone, application of polyacrylamide significantly reduced NH_3 -N volatilization of 37.8%, N_2O -N emission of 35.8% and soil N leaching of 27.1% (Tables 3 and 4). Chen and Shu (2012) also reported that application of polyacrylamide reduced NH_3 -N volatilization by 17%–32% and decreased soil N leaching by 20%–50%. Polyacrylamide is a kind of synthetic polymer. And the polymer skeleton with $-\text{COOH}$, $-\text{OH}$, and $-\text{NH}_2$ hydrophilic groups that have strong water retention capacities can adsorb large quantity of water (Kang et al., 2015). After polyacrylamide is applied into the soil, network structure formed by crosslinking of hydrophilic macromolecule allows N fertilizer molecules or ions such as NH_4^+ -N and NO_3^- -N diffusion to enter (Kumar et al., 2011; Cai et al., 2014). Large molecules polymer molecules or ions can be wrapped into the internal network structure and activated by exchange adsorption, charge and chelating fixed way, thus being slowly released to soil (Cai et al., 2014; Yang et al., 2017). Secondly, polyacrylamide active groups can interact with ions on the surface of soil particles to form a water-stable aggregate structure that further increases the holding effect of soil on nutrients and reduces soil N losses (Jiang et al., 2010; Mamedov et al., 2010; Liu et al., 2015). Thirdly, polyacrylamide in soil is a kind of anion resin that can effectively adsorb NH_4^+ -N and other cationic ions. Adsorption and slow-release effect of polyacrylamide on soil inorganic N are important reasons for reducing soil N losses. Positive impact of polyacrylamide on soil structure stability and its effect on reducing soil N losses are also responsible for a high crop yield (Jiang et al., 2010; Yang et al., 2017). It should be noted that depending on application method and application amount, a large amount of dissolved polyacrylamide can also clog the soil and lead to soil compaction, resulting in a negative impact.

4.2 Soil N balance

In arid and semi-arid regions, external water sources (irrigation and rainfall) and inappropriate use of N fertilizer will inevitably increase soil N losses, resulting in environmental pollution (Huang et al., 2018). Soil N balance reflects the relationship between N input and output in a system (Ladha et al., 2016). In last decades, soil N balance has become an important indicator for regional agricultural N management (Vitousek et al., 2009). In this study, we only consider the input of chemical N fertilizer due to the little amount of inputs from rainfall and irrigation. We were unable to measure N fixation of microorganisms and dry N deposition due to experimental limitation, thus, the system's N input in this study may be underestimated. For the denitrification loss of N, we only measured N_2O -N emission from the soil and underestimated the actual denitrification loss of N, resulting in a higher value of soil N losses. Therefore, the actual value of N surplus in soil may be higher than that given in Table 6. Under optimized fertilization, soil residual inorganic N was relatively small, and total N concentration also maintained at a stable level in maize–wheat rotation system (Table 5).

5 Conclusions

We found that soil amendments significantly increased yield and reduced soil N surplus. Among

the three types of amendments, the performance of FB and FP was the best. Therefore, we recommend that the balance between food production and environmental protection in the HIR can be achieved through the applications of FB and FP.

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